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SOLAR LOAD INPUTS FOR USARIEM THERMAL STRAIN MODELS AND THE SOLAR RADIATION-SENSITIVE COMPONENTS OF THE WBGT INDEX

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13. ABSTRACT *(Maximum 200 words)*

This report describes processes we have implemented to use global pyranometer-based estimates of mean radiant temperature as the common solar load input for the Scenario model, the USARIEM heat strain model, and for the computation of the solar radiation sensitive components of the Wet Bulb Globe Temperature (WBGT) index. For estimating mean radiant temperature from weather station pyranometer data we propose:

$$T_{mrk} = [T_{dbk}^4 + (Py(1+a_{gr}) + \varepsilon_{gr} \cdot \sigma (T_{grk}^4 - T_{dbk}^4))/ 2\sigma]^{1/4} \quad {}^oK$$

where T_{mrk} is the mean radiant temperature in ^oK, Py is the Pyranometer reading in $W{\cdot}m^{-2}$, T_{dbk} is dry bulb temperature in ^oK, T_{grk} is ground surface temperature in ^oK, ε_{gr} is ground surface emissivity, a_{gr} is ground surface albedo, and σ is the Boltzman constant, $5.67 \times 10^{-8}\ W{\cdot}m^{-2}{\cdot}{}^oK^{-4}$.

To replace the category-based solar load inputs to the USARIEM heat strain model, we propose a continuous function:

$$R_{sol} = -0.071(T_{mr} - T_{db})^2 + 10.432\,(T_{mr} - T_{db}) \quad \text{Watts}$$

where R_{sol} is the total radiant load impinging on the outer surface of clothing in Watts, T_{mr} is the mean radiant temperature in ^oC, and T_{db} is dry bulb temperature in ^oC.

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EXECUTIVE SUMMARY

This report summarizes work we have undertaken to assemble a suite of practical mathematical tools that allow a consistent translation of standard weather station data to physiologically relevant input streams for our thermal strain prediction models. Although weather station measurements of air temperature, relative humidity/dew point, and wind speed can be input with minimal pre-processing into most thermal strain models, the solar radiation component, typically measured in Watts/m^2 by an up-looking pyranometer, can not. This report draws extensively on previously published work and describes processes we have currently implemented to use global pyranometer-based estimates of mean radiant temperature as the common solar load input for the Scenario model, the USARIEM heat strain model, and for the computation of the solar radiation sensitive components of the Wet Bulb Globe Temperature (WBGT) index.

The Mean radiant temperature approach averages multiple directional radiant load components to provide a single uniform surface temperature of an imaginary spherical enclosure surrounding the object. For estimating mean radiant temperature from weather station pyranometer data we propose:

$$T_{mrk} = [T_{dbk}^4 + (Py(1+ a_{gr}) + \varepsilon_{gr} \bullet \sigma (T_{grk}^4 - T_{dbk}^4))/ 2\sigma]^{1/4} \qquad {}^oK$$

where T_{mrk} is the mean radiant temperature in ^oK, Py is the Pyranometer reading in W•m^{-2}, T_{dbk} is dry bulb temperature in ^oK, T_{grk} is ground surface temperature in ^oK, ε_{gr} is ground surface emissivity (0.7 to 0.9), a_{gr} is ground surface albedo (0.05 to 0.4), and σ is the Stefan Boltzman constant, $5.67 \bullet 10^{-8}$ W•m^{-2}• $^oK^{-4}$.

There is a need to replace the category-based solar load inputs to the USARIEM heat strain model. We propose a continuous function, based on mean radiant temperature that provides a smoothed best fit to the categories across the natural solar radiation domain:

$$R_{sol} = -0.071 \bullet (T_{mr} - T_{db})^2 + 10.432 \bullet (T_{mr} - T_{db}) \qquad \text{Watts}$$

where R_{sol} is the total radiant load impinging on the outer surface of clothing in Watts, T_{mr} is the mean radiant temperature in ^oC, and T_{db} is dry bulb temperature in ^oC.

Proposed methods for computing the black globe and natural wet bulb temperature components of the WBGT index from mean radiant temperature and the other standard weather measurements are described and documented with appropriate literature citations.

INTRODUCTION

OVERVIEW

Strategies for quantifying solar load are incorporated in human thermal strain prediction models and environmental stress indexes such as the wet bulb globe temperature (WBGT) index. The complex asymmetrical characteristics of most naturally occurring radiant fields has led to the application of a range of sensor systems as potential measurement solutions (2, 3, 4, 12, 13, 17). Sensors such as the black globe temperature thermometer and more elaborate multi-directional radiation sensing systems provide the basis for evaluating solar load. Although a simple global pyranometer sensor is frequently available on standard military and civil weather stations, the black globe thermometer and more sophisticated directional thermal radiation sensing systems are not. There is therefore a continuing need to assemble practical methods to translate what is available from standard weather stations to a physiologically relevant context. Simplified methods to produce an accepted intermediate metric would provide a common thread that facilitates a consistent, coherent computation of solar load components as they are represented both in the indexes and the more sophisticated thermal strain prediction models. This report draws extensively on previously published work and describes processes we have currently implemented to use global pyranometer-based estimates of mean radiant temperature as the common solar load input for the Scenario model, the USARIEM heat strain model, and for the computation of the solar radiation sensitive components of the WBGT index.

Scenario Model

Mean radiant temperature is the solar load input parameter for the Scenario model (7, 8, 9). Derivation of mean radiant temperature from the pyranometer reading completes the radiant load input stream requirements for Scenario.

USARIEM Heat Strain Model

Input of the solar load component of heat stress for the original USARIEM model (15) is based on user specification of one of four broad solar categories: Darkness, Cloudy, Partly Cloudy, or Full Sun. Internally, the category is then related to two factors, SlrF and CldF, the numerical product of which provides a quantitatively discreet "band" intended to represent the total solar radiation (Watts) impinging on the outer clothing surface. This value is subsequently multiplied by a solar efficiency factor, U, that accounts for the effects of clothing and wind speed on solar load actually received by the body (3). The category approach is a reasonable and pragmatic solution to situations where direct quantitative measurements of the radiant components are unavailable and reflects the philosophy of the calculator-based instantiation of the model which depended entirely on externally obtained environmental measurements or approximations.

Recently, the USARIEM model has been implemented in a hand held Heat Stress Monitor (HSM) as well as the command and control oriented MERCURY test bed system (10, 11). Both of these systems have access to direct or derived measures of ambient solar radiation. In order to exploit these data and automate the model input process, we developed schedules that allow consistent selection of the appropriate solar category. Table 1 shows the categories and the schedule by which they were initially selected: in MERCURY from a pyranometer measurement of global solar radiation, and in the HSM from mean radiant temperature (T_{mr}) derived from air temperature (T_{db}), wind speed (V_a) and black globe (T_g) measurements.

Table 1. Category-based classification schedule for USARIEM model solar loads.

Category	SlrF (W)	CldF	SlrF•CldF (W)	Pyranometer (W/m^2)	T_{mr} - T_{db} (^{o}C)
Darkness	0.0	4.0	0	<150	<10
Cloudy	50.0	3.5	175	150 to 399	10 to 24.9
Partly Cloudy	90.0	3.0	270	400 to 700	25 to 45
Full Sun	150.0	2.5	375	>700	>45

<u>**Statement of the Problem**</u>

It was found during sensitivity studies using the USARIEM model implementation for the Heat Stress Monitor (HSM), that the category approach creates disturbing discontinuities in work/rest cycle and maximum safe work time outputs when the solar load suddenly shifts to a new category. We therefore decided to replace the category based solar load input schedule with a continuous function that would, in addition, more fully exploit the currently available solar load- related measurements available to both the HSM and MERCURY's successor system, the Operational Medicine Environmental Grid Applications (OMEGA) Test bed.

OBJECTIVES AND APPROACH

<u>**Objectives**</u>

The fundamental objective is to document processes we have used to derive mean radiant temperature from global pyranometer data sets. The mean radiant temperature approach averages multiple directional radiant load components to provide a single uniform surface temperature of an imaginary spherical enclosure surrounding the object. A key objective for the USARIEM heat strain model applications in the HSM and OMEGA is to document methodology for an empirically derived continuous solar load input parameter, R_{sol}, that is based on mean radiant temperature, T_{mr}, and essentially overlays that model's category-based solar load inputs. The intent is to preserve, for

better or worse, the quantitative trends explicit in the category-based handling of solar load and to achieve a historically consistent but significantly smoother quantitative representation of this model input across the solar load domain. The primary objective for the WBGT index components is to document those mathematical relationships we have adopted for estimating black globe and natural wet bulb temperatures using T_{mr}.

Approach

The approach is to employ regression analysis to establish a smooth fit to the category products using T_{mr} as the common intermediate parameter for solar load inputs to both the HSM and OMEGA model instantiations. Because T_{mr} is easily derived from the HSM's black globe, air temperature and wind speed measurements using standard published equations (1), this report will focus on methodologies for approximating T_{mr} from pyranometer data. A significant collateral benefit of pyranometer-derived T_{mr} is that, in conjunction with the other standard meteorological measurements of air temperature, humidity, and wind speed, it is possible to estimate black globe temperature (T_g), and the naturally convected wet bulb temperature (T_{nwb}) which are the two primary components of the WBGT index. In spite of known limitations, WBGT continues to be the preferred heat stress management tool within the military preventive medicine community. Its inclusion as an ancillary product in more rational predictive model output streams (14) is desirable because the ability to demonstrate inadequacies of this culturally entrenched frame of reference is essential to wider acceptance of rational models. Our approach, based on pyranometer-derived T_{mr}, is thus intended to provide a coherent sensor fusion methodology for linkage of standard meteorological sensor systems to the WBGT and to the more rigorous thermal strain prediction models.

METHODS

ANALYTICAL PROCEDURES AND SENSOR SYSTEMS

This work is intended to document the historical and analytical basis for changes in the solar load related software modules currently or soon to be instantiated in USARIEM's thermal strain predictive models. The methodologies developed in the results section are based on analysis of data obtainable from sensor systems commonly available on weather station platforms: Air temperature, relative humidity, wind speed, and solar radiation sensors comprise the core suite of sensors for current thermal strain prediction models. The analytical focus is the extraction of physiologically-relevant solar load information from pyranometer data. In clear sky situations, readings from these sensors range typically from slightly below 0 at night to more than 1000 $W*m^{-2}$ at mid day. Data from up-looking pyranometers are available from automated weather station systems such as the Remote Automated Weather Stations (RAWS) system at Eglin AFB, Florida and USARIEM's new portable RAWS system that supports OMEGA and the Warfighter Physiological Status

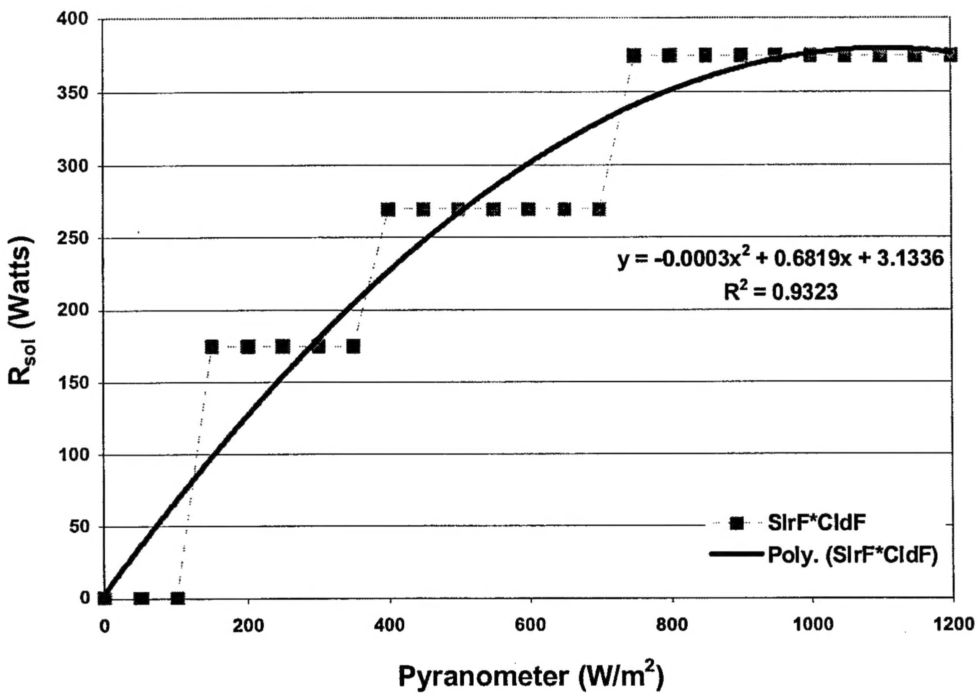
Monitoring (WPSM). Statistical evaluations and regression analyses required for this effort were accomplished using tools available in Microsoft Excel/Office 2000 TM.

RESULTS

USARIEM MODEL AND PYRANOMETER DATA

A direct relationship between the pyranometer reading and the SlrF•CldF product was derived using a polynomial regression fit as shown in Figure 1. As a smoothed representation of the SlrF•CldF product, the variable R_{sol} quantifies the extra radiation impinging on the outer surface of the clothing in Watts, for conditions where air and radiant temperature differ. It is important to note that R_{sol} reflects significant assumptions about the effects of high sun angles on projected area of a standing person.

Figure 1. R_{sol} : A polynomial fit of category-based solar load to pyranometer readings.



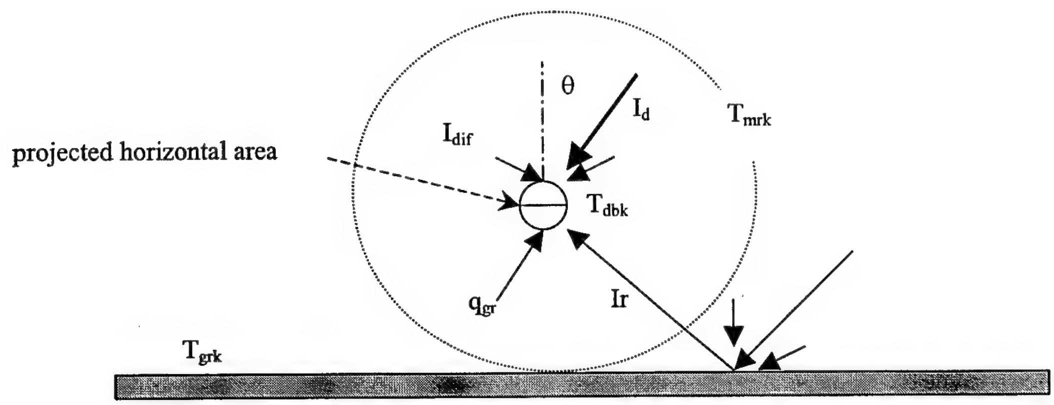
MEAN RADIANT TEMPERATURE

The pyranometer and air temperature measurements from the Remote Automated Weather Stations (RAWS) are used as the basis for estimating T_{mr}. Using the pyranometer reading to compute a mean radiant temperature provides significant advantages over the direct empirical fit described above. It allows consideration of other indirect but related radiant load components and has more general utility as an input parameter for predictive models such as Scenario and for the WBGT derivation algorithms. Because it is unrealistic to assume that all

of the radiant load is coming from the sky hemisphere and is measured by the up-looking pyranometer, additional measurements or reasonable assumptions are in order to account for reflected solar radiation and upwelling long wave radiation from the heated ground surface. An isotropic mean radiant field is estimated, as the sum of the 4π contributions of each of these elements. Note that temperature units for dry bulb temperature, ground temperature, and mean radiant temperature calculations are degrees Kelvin ($^{O}K = {}^{O}C + 273.15$).

Figure 2 is a schematic of a mean radiant temperature (T_{mrk}) representation of the radiation received by an above ground radiantly black object at air temperature (T_{dbk}). The object receives direct and ground reflected solar radiation and long wave radiation from the ground.

Figure 2. Schematic of radiation received by an above ground object.



The angle of incidence of the direct solar beam radiation is θ. The direct (I_d) and diffuse (I_{dif}) solar radiation are incident on the projected up-looking horizontal area (A_{up}) of the object. The total intensity received is ($I_d \cdot \cos\theta + I_{dif}$) which is assumed to equal the incident radiation intensity (Py) measured by a skyward looking horizontal pyrometer.

The solar radiation reflected from the ground to the underside of the object is $A_{down} \cdot I_r$, where I_r is the direct and diffuse solar radiation reflected by the ground. It is represented as a_{gr}*Py where a_{gr} is the ground's albedo or its hemispherical solar reflectance. Representative values for the albedo of some common surfaces, from Holman (6), are given in Table 2.

Table 2. Albedos for some natural surfaces (From Holman, 1997).

Surface	Albedo
Water	0.3-0.4
Black dry soil	0.14
Black moist soil	0.08
Gray dry soil	0.25-0.30
Gray moist soil	0.10-0.12
Desert loam	0.29-0.31
Bright fine sand	0.37
Snow	0.4-0.85
Green grass	0.26

Further, the underside of the reference object may also receive radiant heat (q_{gr}) from the ground.

$$q_{gr} = \varepsilon_{gr} \bullet \sigma \left(T_{grk}^4 - T_{dbk}^4 \right) \qquad \text{Watts} \qquad \text{(Eq.1)}$$

where ε_{gr} is the long wave (low temperature) emissivity of the ground. For opaque materials absorptivity equals emissivity and some representative values from Holman (6) are listed in Table 3.

Table 3. Absorptivities / emissivities of various surfaces to solar and long wave radiation (From Holman, 1997).

Surface	solar	long wave
Aluminum, highly polished	0.15	0.04
Copper, highly polished	0.18	0.03
Tarnished	0.65	0.75
Cast iron	0.95	0.21
Stainless steel, no. 301, polished	0.37	0.60
White marble	0.46	0.95
Asphalt	0.90	0.90
Red brick	0.75	0.93
Gravel	0.29	0.85
White paint	0.12-0.16	0.90-0.95

The radiant energy depicted in Figure 2 can be mathematically represented as:

$$(A_{up}+A_{down}) \bullet \sigma \left(T_{mrk}^4 - T_{dbk}^4\right) = A_{up} \left(I_d \bullet \cos\theta + I_{dif}\right) + A_{down} \left(I_r + q_{gr}\right) \qquad \text{(Eq.2)}$$

The projected areas facing up and down must be equal ($A_{up} = A_{down} = A$) simplifying Eq. 2 to:

$$2A \bullet \sigma\,(T_{mrk}^4 - T_{dbk}^4) = A(I_d \bullet \cos\theta + I_{dif}) + A\,(I_r + q_{gr}) \qquad \text{(Eq.3)}$$

Then substituting the Pyrometer reading (Py) and simplifying:

$$2\sigma\,(T_{mrk}^4 - T_{dbk}^4) = Py\,(1 + a_{gr}) + \varepsilon_{gr} \bullet \sigma\,(T_{grk}^4 - T_{dbk}^4) \qquad \text{(Eq.4)}$$

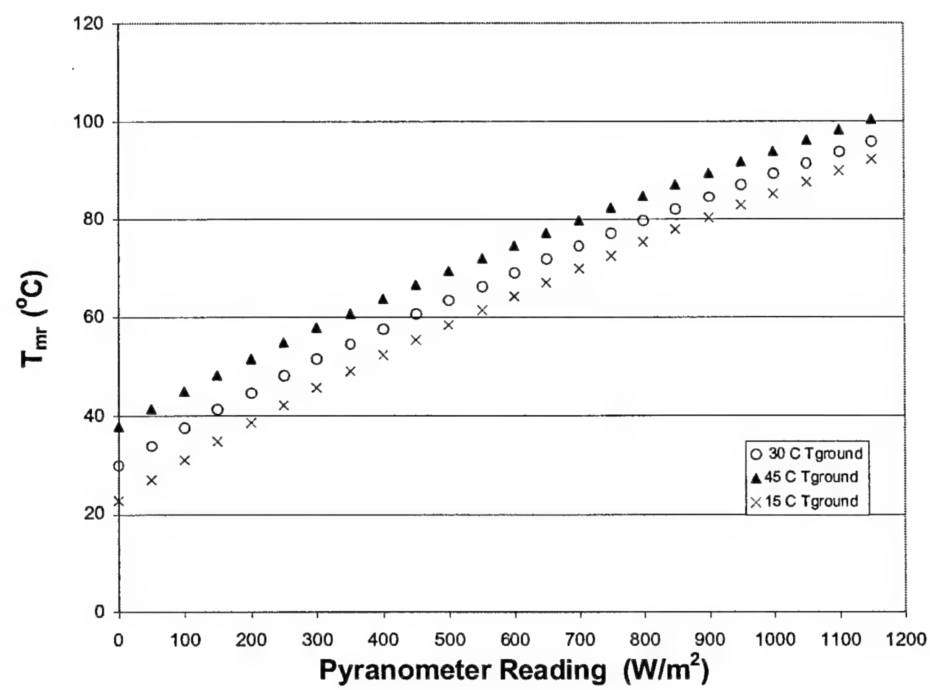
or

$$T_{mrk} = [T_{dbk}^4 + (Py(1 + a_{gr}) + \varepsilon_{gr} \bullet \sigma\,(T_{grk}^4 - T_{dbk}^4))/\,2\sigma\,]^{1/4} \quad {}^{o}K \qquad \text{(Eq.5)}$$

where:

T_{mrk} = mean radiant temperature, ^{o}K
Py = pyranometer reading, $W \bullet m^{-2}$
T_{dbk} = dry bulb temperature, ^{o}K
T_{grk} = ground surface temperature, ^{o}K
ε_{gr} = ground surface emissivity
a_{gr} = ground surface albedo
σ = Stefan Boltzman constant, $5.67 \times 10^{-8}\ W \bullet m^{-2} \bullet {}^{o}K^{-4}$

Figure 3. Effects of ground temperature on estimated mean radiant temperature at constant 30 ^{O} air temperature.



Ground surface temperature measurements are provided by RAWS systems and reasonable approximations for bare ground albedo and long wave emissivity can

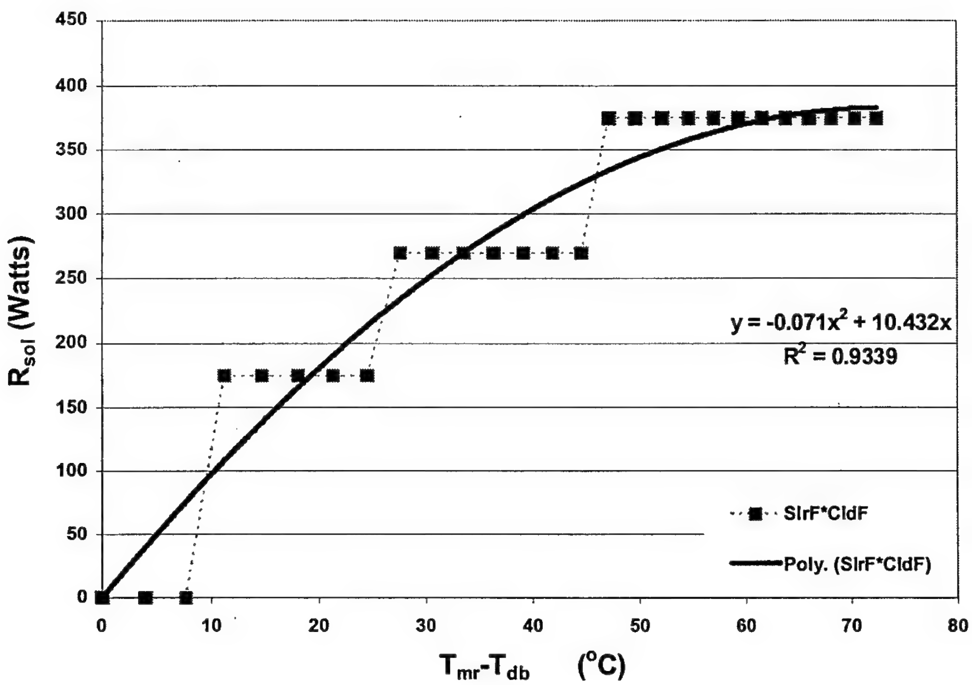
be obtained from Tables 2 and 3. Note that if the ground albedo is assumed to be 0 and the ground temperature equals air temperature eq. 5 simplifies to:

$$T_{mrk} = (T_{dbk}^4 + Py)/ 2\sigma)^{1/4} \qquad {}^{o}K \qquad \text{(Eq.6)}$$

USARIEM MODEL AND MEAN RADIANT TEMPERATURE

Using $T_{mr} - T_{db}$ categories from Table 1, regression analysis yields a continuous, smoothed function that overlays the USARIEM model's category-based solar load as shown in Figure 4.

Figure 4. R_{sol}: A polynomial fit of category-based solar load to $T_{mr} - T_{db}$.



Polynomial regression yields:

$$R_{sol} = -0.071\ (T_{mr} - T_{db})^2 + 10.432\ (T_{mr} - T_{db}) \qquad \text{Watts} \qquad \text{(Eq.7)}$$

The continuous variable R_{sol} here represents a "plug-in" replacement for the SlrF•CldF product in the USARIEM heat strain model algorithm that, along with the solar efficiency factor, U, is used to compute the actual radiant load on the body. While it appears to be a reasonable approximation of the USARIEM model's handling of solar load, it is probably appropriate to characterize the magnitude of departures from a more generalized rational estimate such as Gagge's Effective Radiant Flux (ERF).

Effective Radiant Flux (ERF)

Effective Radiant Flux (Santee and Gonzalez, 1988) is similar to R_{sol} in that it represents solar load as a function of air temperature and mean radiant temperature, but it also includes terms for clothing absorptivity and radiating surface area. We compute whole body ERF as follows:

$$ERF = \sigma \cdot \alpha \cdot A_r / A_D \cdot (T_{mrk}^4 - T_{dbk}^4) \cdot A_D \quad \text{Watts} \qquad \text{(Eq.8)}$$

Where,

T_{dbk} = dry bulb temperature, ^oK

α = absorptivity of clothing, here 0.9

σ = Stefan Boltzman constant, $5.67 \times 10^{-8}\ W \cdot m^{-2} \cdot {}^oK^{-4}$

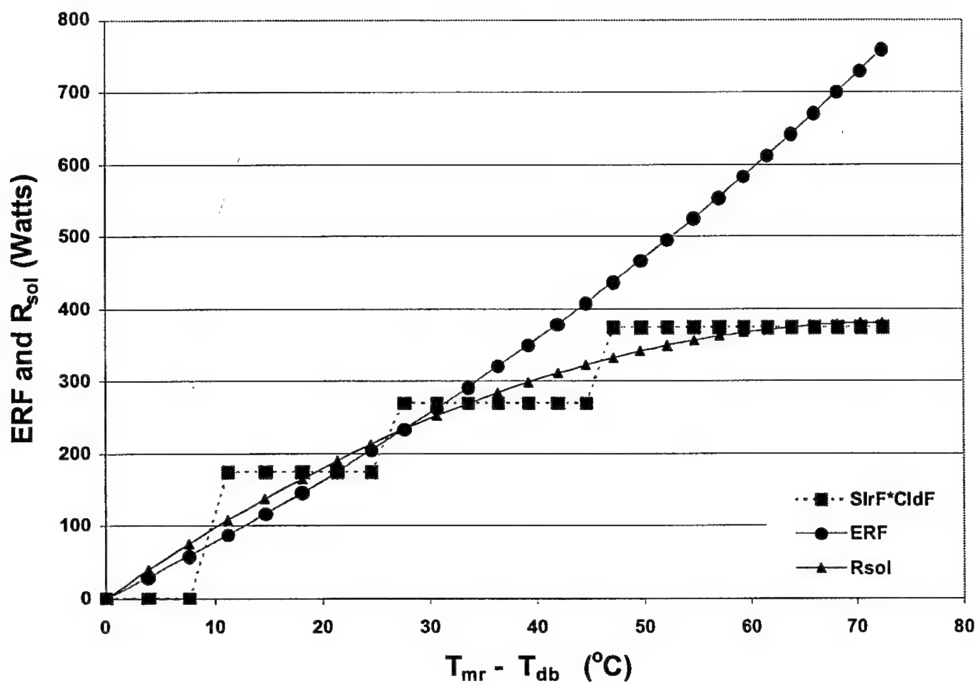
T_{mrk} = mean radiant temperature, ^oK

A_D = Dubois body surface area, here 1.8 m^2

A_r / A_D = ratio of radiating surface to total body surface area, 0.72

Figure 5 shows the relationship between ERF and the SlrF•CldF product.

Figure 5. Comparison of Effective Radiant Flux (ERF) and R_{sol} as a function of T_{mr} - T_{db}.



Aside from the fact that clothing effects on net solar load burden in the USARIEM model are computed following the estimate of R_{sol}, it is clear that significant implicit assumptions about view angle, solar altitude, and posture are aggregated in the category factors The difference between the computed ERF and Rsol is shown in Figure 6.

Figure 6. Difference between ERF and R_{sol} as a function of $T_{mr} - T_{db}$.

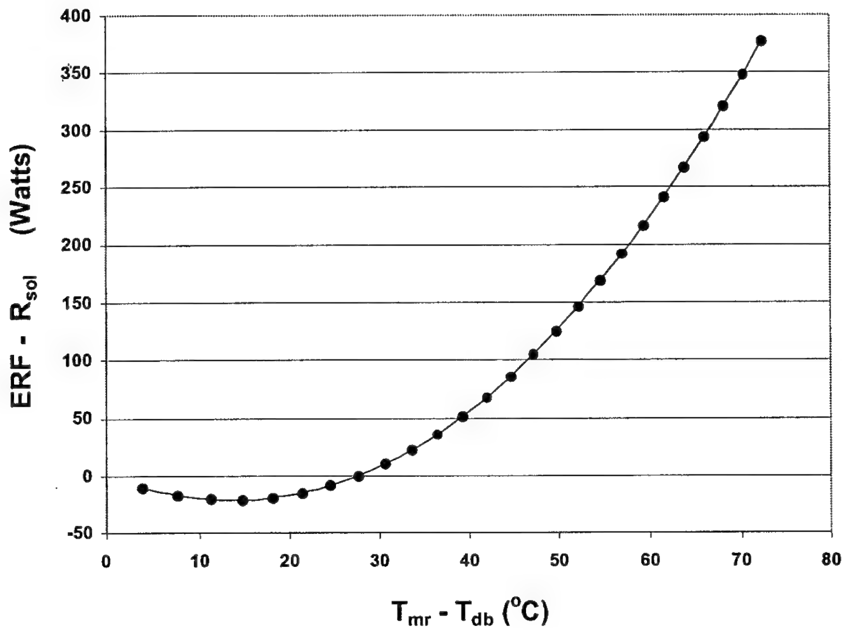


Figure 7. Adjustment factor for ERF as a function of $T_{mr} - T_{db}$.

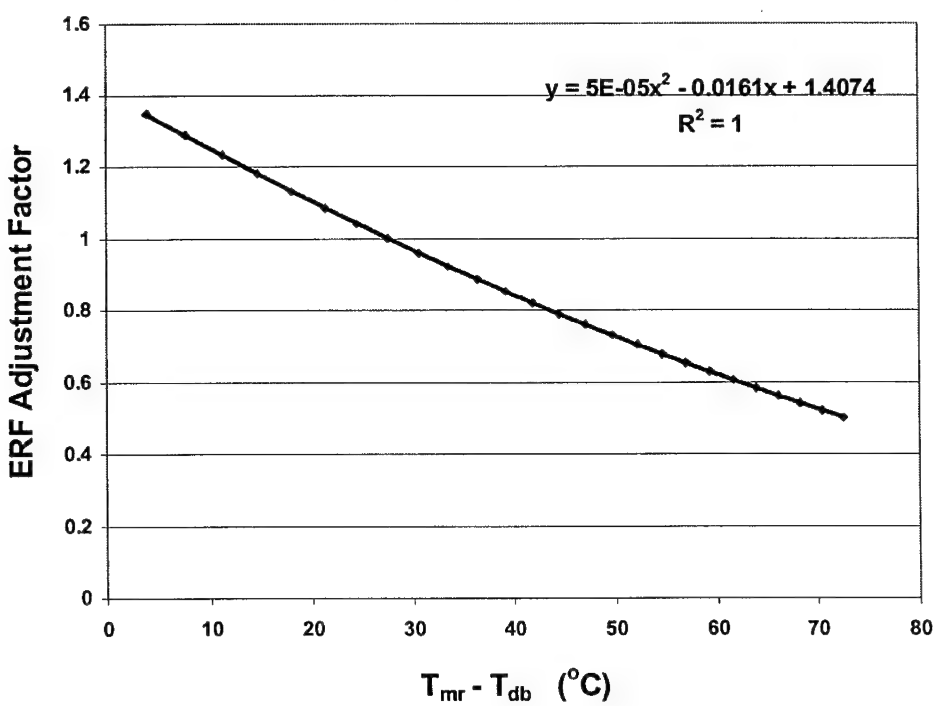


Figure 7 depicts the polynomial regression function that yields an adjustment factor/multiplier for ERF that quantifies the difference between ERF and Rsol across the solar load domain. The ERF multiplier ranges from 1.4 to roughly 0.45 at the highest solar load.

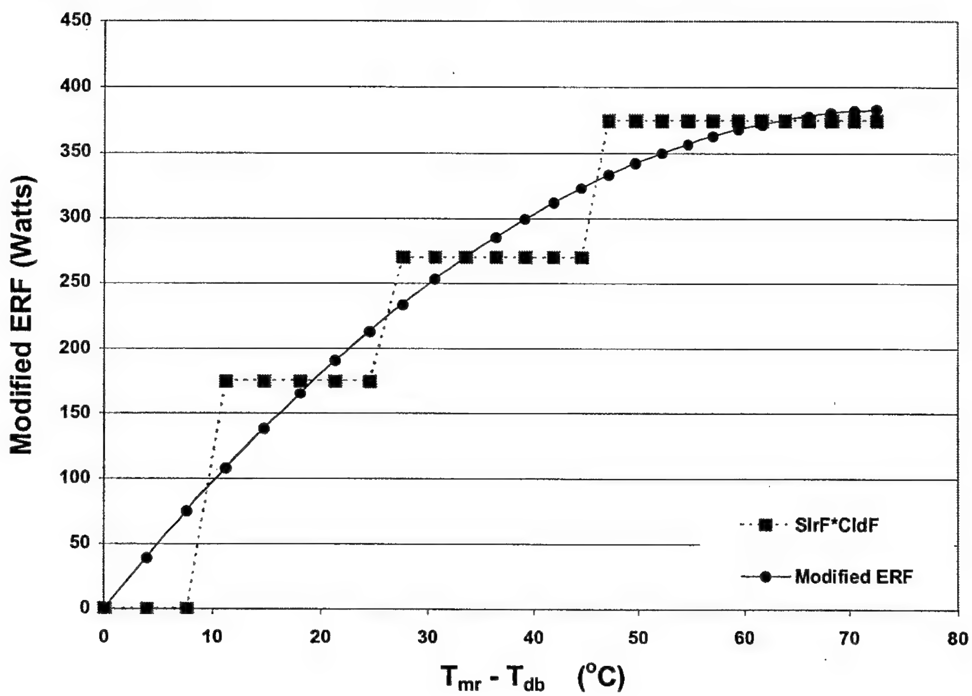
The expression modifying ERF and relating ERF to R_{sol} thus becomes:

Modified ERF =

R_{sol} = ERF • $(0.00005\,(T_{mr} - T_{db})^2 - 0.0161\,(T_{mr} - T_{db}) + 1.4)$ Watts (Eq.9)

Figure 8 shows the modified ERF across the solar load domain.

Figure 8. Modified ERF as a function of $T_{mr} - T_{db}$.



Although the preceding exercise characterizes the relationship between ERF and R_{sol}, and would allow direct compatibility with the USARIEM heat strain model input stream, applications in OMEGA and the Heat Stress Monitor will use the exclusively empirical fit described previously, Eq. 7:

$R_{sol} = -0.071\,(T_{mr} - T_{db})^2 + 10.432\,(T_{mr} - T_{db})$ Watts

COMPUTATION OF THE WBGT COMPONENTS

The addition of a Wet Bulb Globe Temperature (WBGT) capability for OMEGA does not represent a cutting edge technological improvement for thermal injury risk assessment. It does, however, provide a useful resource to support comparative and analytical evaluations of this widely used heat stress

index. It also provides an important frame of reference and credible historical thread for potential OMEGA users who are currently committed to WBGT-based heat stress management doctrine (16).

Part of the appeal and resilience of WBGT methodology is the simplicity of the basic measurements and the computation of the index. The WBGT index for outdoor environments is computed as follows:

$$WBGT = 0.7T_{nwb} + 0.2T_{g} + 0.1T_{db} \qquad {}^{o}C \text{ or } {}^{o}F \qquad \text{(Eq.10)}$$

Where:

T_{nwb} = Natural Wet Bulb Temperature ^{o}C or ^{o}F
T_{g} = 6 inch Black Globe Temperature ^{o}C or ^{o}F
T_{db} = Air Temperature ^{o}C or ^{o}F

Because two components of the WBGT, naturally convected wet bulb temperature, T_{nwb} , and black globe temperature, T_{g} , are not measured by standard weather stations, these values must be derived from the available measured data. The original conceptual advantage of WBGT in terms of simplicity is certainly lost when these components must be derived from standard measures using iterative computational methods, but the processes can be automated in software. It should be noted that recent development of a regression based equation that uses weather station data to compute an Environmental Strain Index (ESI) has demonstrated very high correlation with measured WBGT values (12). This may ultimately prove to be an acceptable substitute for the more computationally demanding solutions described below.

Natural Wet Bulb Temperature

In the current implementation of OMEGA, the naturally convected wet bulb temperature is computed using an iterative process to solve a previously described equilibrium state equation (5). A first guess for T_{nwbk} ($T_{nwbk\text{-}TEST}$, starting typically at T_{dbk}) is substituted into equation 11 and both sides evaluated. $T_{nwbk\text{-}TEST}$ is incrementally decremented until both sides converge on a value that satisfies the equality, and $T_{nwbk\text{-}TEST}$ equals the true T_{nwbk} . The process uses the derived Mean Radiant Temperature (T_{mrk}), and the air temperature (T_{dbk}), wind speed (V_{a}), and relative humidity (RH) measurements. From Gonzalez et al.:

$$h_{c}(T_{dbk}-T_{nwbk}) + \varepsilon_{nwb} \bullet \sigma \, (T_{mrk}{}^{4} - T_{nwbk}{}^{4}) = h_{e}(P_{snwb} - (RH/100) \bullet P_{sdb}) \qquad \text{(Eq.11)}$$

Where:

h_{c} = convective heat transfer coefficient, $W \bullet m^{-2} \bullet {}^{o}K^{-1}$
T_{dbk} = dry bulb temperature, ^{o}K
T_{nwbk} = natural wet bulb temperature, ^{o}K
ε_{nwb} = emissivity of the surface of the wetted wick, ~ 0.5
σ = Stefan Boltzman constant, 5.67×10^{-8} $W \bullet m^{-2} \bullet {}^{o}K^{-4}$
T_{mrk} = mean radiant temperature, ^{o}K

h_e = evaporative heat transfer coefficient, $W \cdot m^{-2} \cdot Torr^{-1}$
P_{snwb} = saturation water vapor pressure at T_{nwb}, Torr
RH = % RH
P_{sdb} = saturation water vapor pressure at T_{db}, Torr

The convective heat transfer coefficient is computed from wind velocity, V_a, in $m \cdot s^{-1}$:

$$h_c = 42.024\, V_a^{0.466} \qquad W \cdot m^{-2} \cdot {}^oK^{-1} \qquad \text{(Eq.12)}$$

And the evaporative heat transfer coefficient is related to the convective heat transfer coefficient by the Lewis relation:

$$h_e = 2.2\, h_c \qquad W \cdot m^{-2} \cdot Torr^{-1} \qquad \text{(Eq.13)}$$

Saturation water vapor pressures at T_{nwb} and T_{db} are computed using a base 10 version of Antoine's equation for temperatures in ^oC (Santee and Gonzalez, 1988).

$$P = 10^{(8.10765 - 1750.286/(T+235))} \qquad \text{Torr} \qquad \text{(Eq.14)}$$

Black Globe Temperature

In the current implementation of OMEGA, black globe temperature is computed using a previously described equilibrium state equation for the globe, where radiative heat gain equals convective heat loss (ASHRAE, 1984):

$$h_{rg}\,(T_{mrk} - T_{gk}) = h_{cg}\,(T_{gk} - T_{dbk}) \qquad \text{(Eq.15)}$$

or

$$T_{gk} = (h_{cg} \cdot T_{dbk} + h_{rg} \cdot T_{mrk}) / (h_{cg} + h_{rg})$$

Where:

T_{gk} = black globe temperature, ^oK
h_{rg} = linear radiation transfer coefficient for globe
= $\varepsilon_g \cdot \sigma\,(T_{mrk} + T_{dbk}) \cdot (T_{mrk}^2 + T_{dbk}^2)$, $W \cdot m^{-2} \cdot {}^oK^{-1}$
h_{cg} = convective heat transfer coefficient
= $6.32\, D^{-0.4} \cdot V_a^{0.5}$, $W \cdot m^{-2} \cdot {}^oK^{-1}$
ε_g = emissivity of black globe, ~0.95
σ = Stefan Boltzman constant, $5.67 \times 10^{-8}\, W \cdot m^{-2} \cdot {}^oK^{-4}$
T_{dbk} = dry bulb temperature, ^oK
T_{mrk} = mean radiant temperature, ^oK
D = diameter of globe, m
V_a = air velocity, $m \cdot s^{-1}$

DISCUSSION

MODEL INTEGRATION

As the federation of warfighter predictive/performance models required to support Army science and technology objectives becomes more tightly integrated, there is a growing need to define and document practical methods for handling environmental measurements. The ability to leverage existing meteorological resources as input streams for model test and evaluation expands research opportunities, allows early identification of meteorological data gaps or sensor inadequacies, and ultimately contributes to the effective definition of meteorological requirements for highly integrated operational systems such as Land Warrior.

EXPLOITING EXISTING INFRASTRUCTURE

Our efforts here focus on the solar radiation component of the natural environment and the derivation of a commonly accepted, physiologically relevant metric that would support a range of indexes and thermal strain prediction models. The methodology proposed for derivation of T_{mr} from pyranometer data represents a considerable compromise from the most robust biophysical evaluations. Nevertheless, it does provide a practical solution to a data gap that is not likely to be otherwise resolved in the near future. Pyranometers, based on silicon photodiode technology, are widely used solar radiation sensors. Data from up-looking pyranometers are available from automated weather station systems such as the Remote Automated Weather Stations (RAWS) system at Eglin AFB, Florida and USARIEM's new portable RAWS system that supports OMEGA and the Warfighter Physiological Status Monitoring (WPSM) project.

CONCLUSIONS

There is a growing need to exploit existing standard weather station data resources to support emerging requirements for real time-modeling of Warfighter thermal, hydration, and performance status.

Combined with standard measurements of air temperature, humidity, and wind speed, a practical method to derive mean radiant temperature from weather station pyranometer readings provides a basic input stream for thermal strain prediction models and provides opportunities for physiologically relevant sensor fusion.

The proposed expression relating pyranometer readings to mean radiant temperature provides a common thread for consistent utilization of standard meteorological data for automated input of solar load to the Scenario and USARIEM heat strain models.

The proposed expression relating pyranometer readings to mean radiant temperature provides a common thread for consistent utilization of standard meteorological data for rational estimation of the individual components of the traditional Wet Bulb Globe Temperature (WBGT) index.

The proposed continuous function relating mean radiant temperature to the category-based solar load input in the USARIEM heat strain model provides a practical solution for linkage of that model to standard weather data resources.

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